Test-beam results of a fibre sampling Dual-Readout Calorimeter prototype

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on behalf of the

HiDRa Collaboration

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AIDA innova

HiDRa for FCCee

- FCCee physics: aim for high precision measurements of Higgs and electroweak physics
    - Target **hadronic sampling term** for energy resolution ⇒ $\frac{\sigma}{E} \sim \frac{30\,\%}{\sqrt{E}}$

- The HiDRa collaboration aims to develop a **Dual-Readout** Calorimeter for EM and HAD calorimetry.
    - Dual Readout**:** dual sampling of the calorimeter signal utilizing two sensitive materials with different response characteristics—such as scintillating and Cherenkov fibers—enabling event-by-event correction of the electromagnetic component fluctuations, recovering signal linearity and improving energy resolution
    - **Electromagnetic sampling term** from Geant4 Simulation ⇒ $\frac{\sigma}{E} \sim \frac{15\,\%}{\sqrt{E}}$

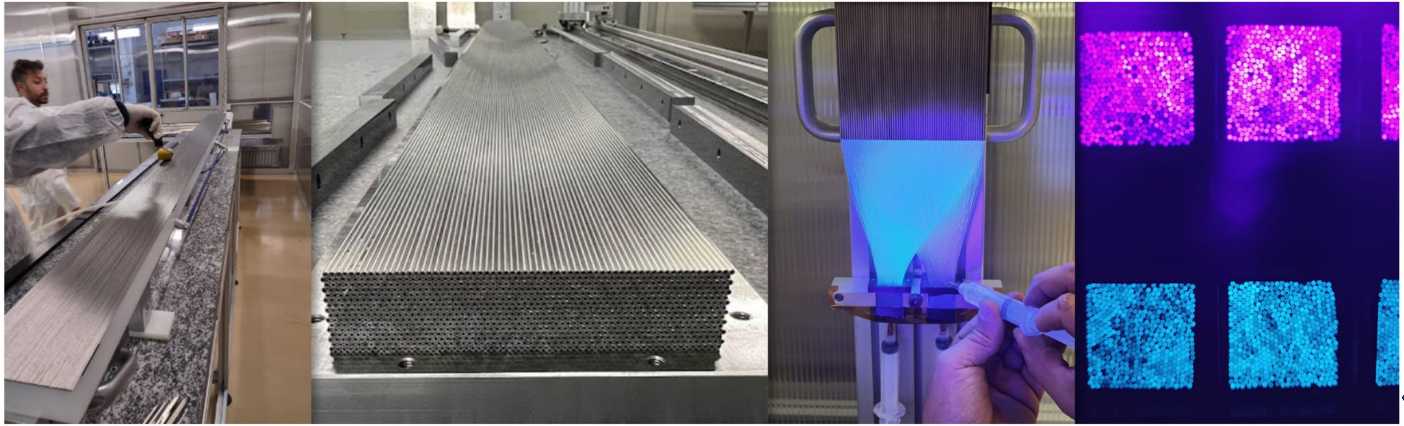
- Ongoing research: starting from 2012.
    - N. Akchurin et al. The electromagnetic performance of the RD52 fiber calorimeter. Nucl. Instrum. Meth. A, 735:130–144, 2014.
    - N. Ampilogov et al. Exposing a fibre-based dual-readout calorimeter to a positron beam. JINST, 18(09):P09021, 2023.

Dual Readout prototype: HiDRa

Assembly site at Pavia INFN laboratories.

Capillary tubes gluing process

Scintillating and Cherenkov fibers are collected separately



Module ready for fiber insertion

Scintillating and Cherenkov fiber batches prepared for PMT integration

Test Beam 2024 campaign

Complete HiDRa: Consists of 80 modules for nearly complete hadronic shower containment.

2024 Test Beam Setup:

- 36 out of 80 modules were used, arranged in 3 columns x 12 rows.
- Active volume: 38.4 x 33.6 x 250 cm³ (~50% of the full HiDRa), ⇒ **only EM** shower containment.
- PMT readout

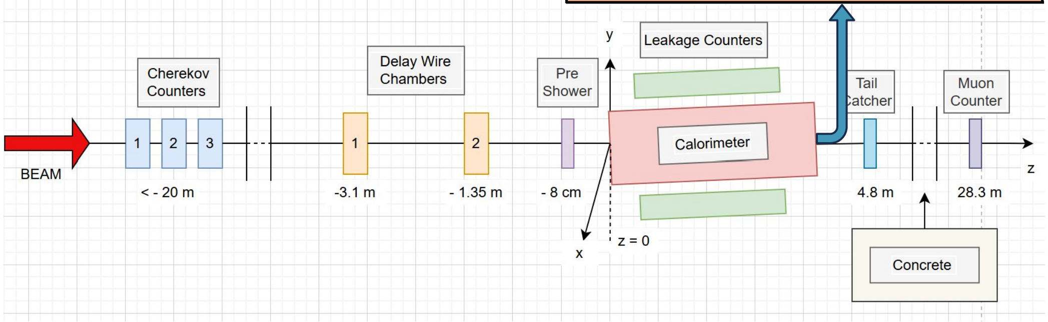
Prototype Test at CERN:
Positrons: E ∈ [10, 120] GeV, Muons: E ∈ [120, 170] GeV, Pions: E ∈ [20, 120] GeV

TS55	TC55	TS54	TC54	TS53	TC53
TS45	TC45	TS44	TC44	TS43	TC43
TS35	TC35	TS34	TC34	TS33	TC33
TS25	TC25	TS24	TC24	TS23	TC23
TS16	TC16	TS15	TC15	TS14	TC14
TS17	TC17	TS00	TC00	TS13	TC13
TS10	TC10	TS11	TC11	TS12	TC12
TS20	TC20	TS21	TC21	TS22	TC22
TS30	TC30	TS31	TC31	TS32	TC32
TS40	TC40	TS41	TC41	TS42	TC42
TS50	TC50	TS51	TC51	TS52	TC52
TS60	TC60	TS61	TC61	TS62	TC62

Module Equalisation: with equalisation runs at the centre of each minimodule.

Calibration: total energy measured—separately for scintillation and Cherenkov signals—matches the beam energy.

Electron Selection Procedure: Established with auxiliary detectors for data analysis.

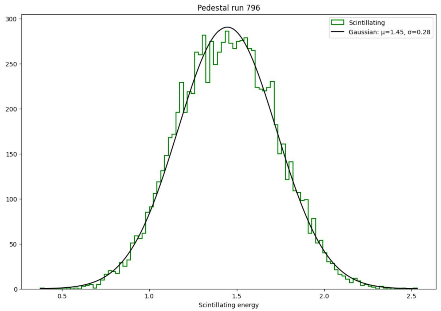


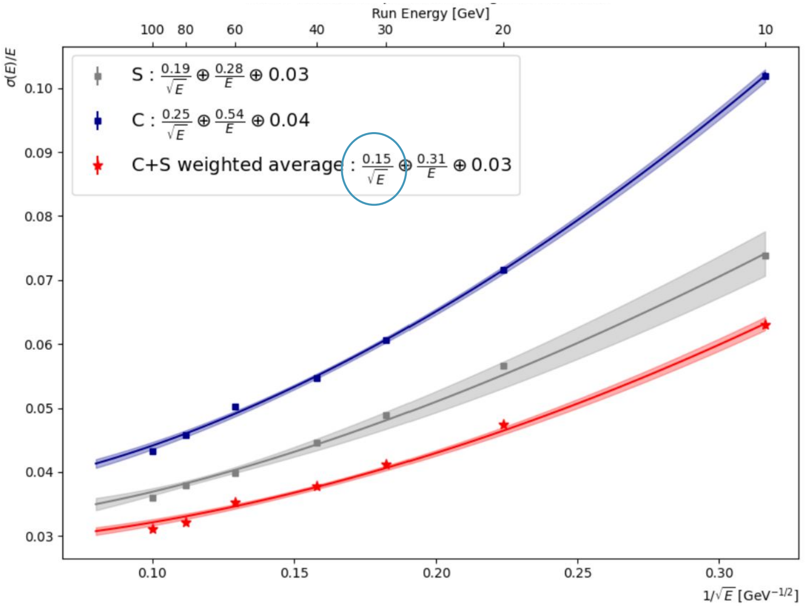
Test Beam 2024: energy resolution

EM sampling term from simulation 15%/√E achieved

Step in Data analysis:

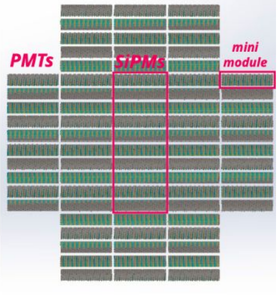
- **Linear calibration** to optimize resolution
- C+S signals combined with weighted average
- **Resolution fit** performed according to $\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$
    - Noise term b fixed with pedestal runs

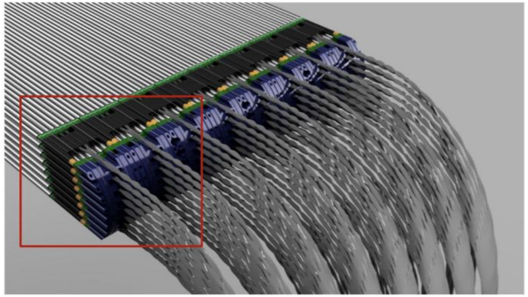




Conclusion

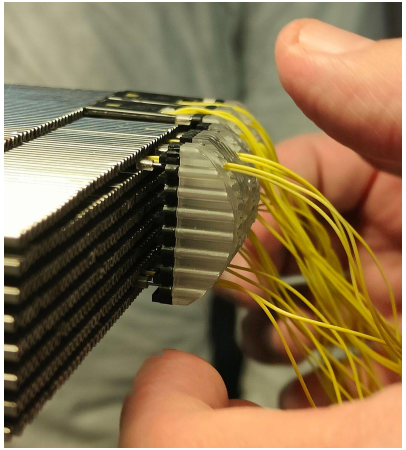
- Dual-Readout fiber based calorimeter is a good candidate for FCCee;
- Successful prototype construction and Test Beam campaign in 2024;
- **Electromagnetic resolution** of ~ **15%/√E** has been **achieved** (preliminary)

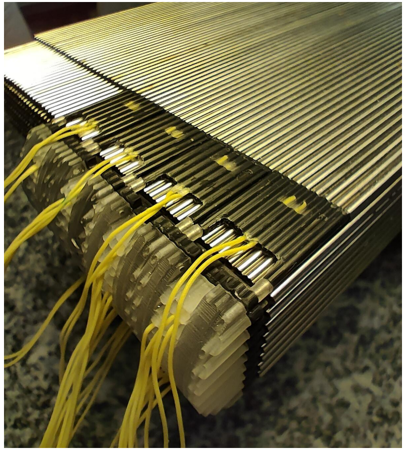




… 2025

- Finalization of HiDRa prototype for **hadronic containment**
  - SiPM integration and readout
- Future test beam in summer 2025 to measure **hadronic resolution**

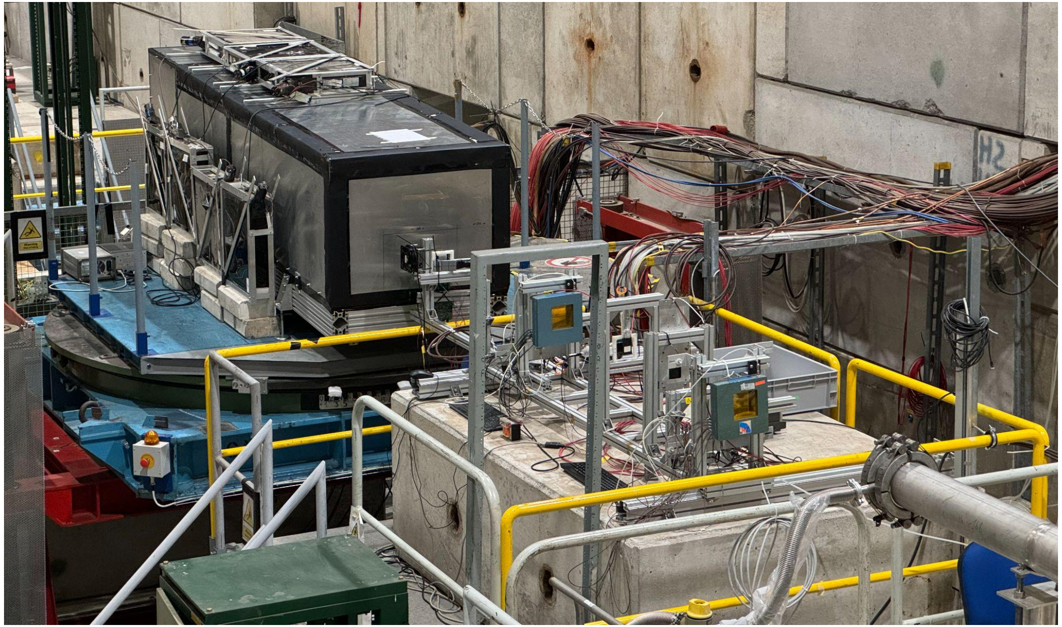




BACKUP

Thank you for your attention!

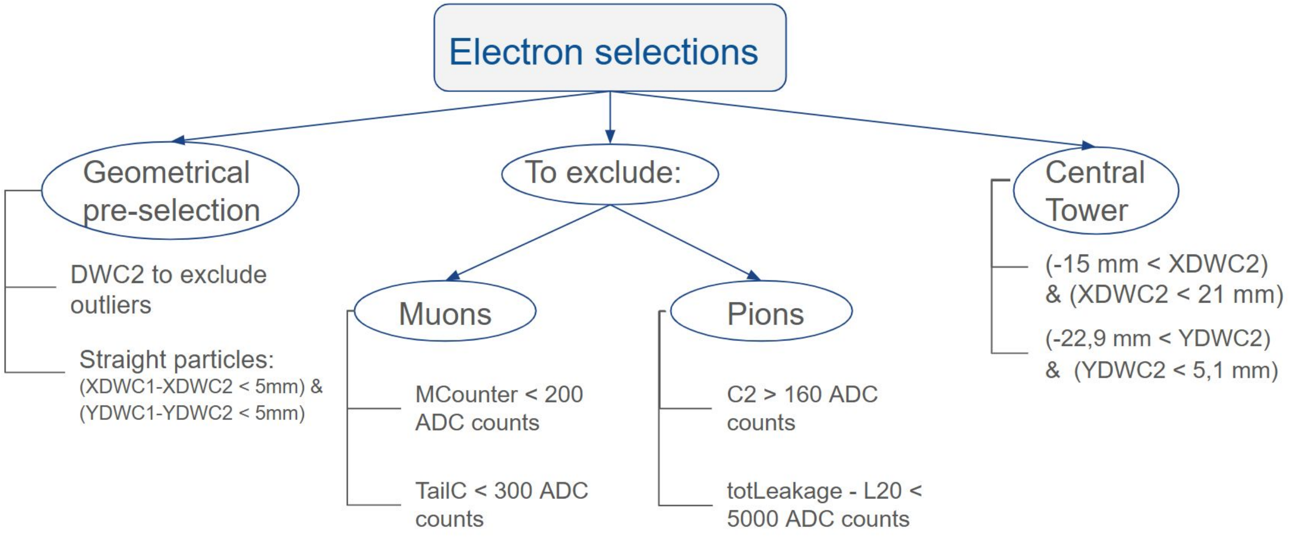
Beam Line During TB 2024 Campaign



- For **further information:**
  https://twiki.cern.ch/twiki/bin/view/DREAM/DreamTBAugust2024

Proposed selection(s)

- We have studied the response of the ancillary detectors during TB 2024.
- We propose the **following selections** to keep only electrons:

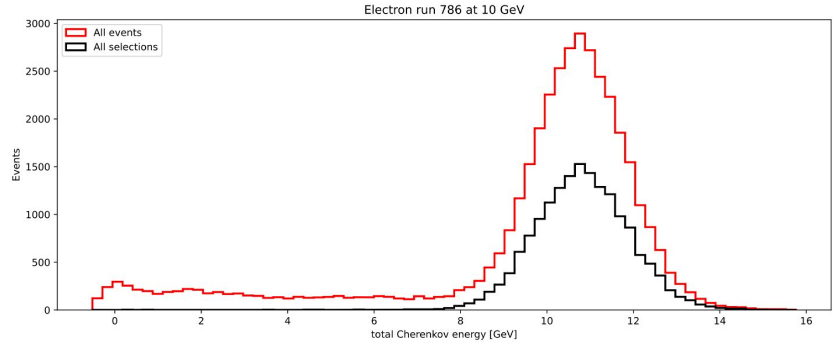


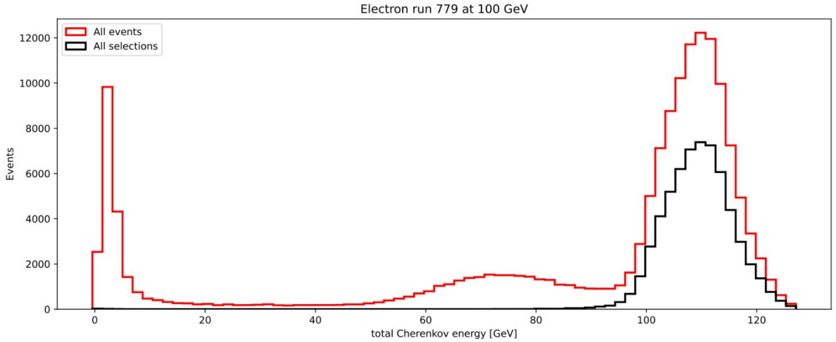
- For **further information:** https://indico.cern.ch/event/1477827/contributions/6224496/subcontributions/515584/attachments/2966424/5219159/Report%2013_11_24.pdf

Selection: consequences on total Cherenkov energy

Selection **efficiency** for **electron** runs:

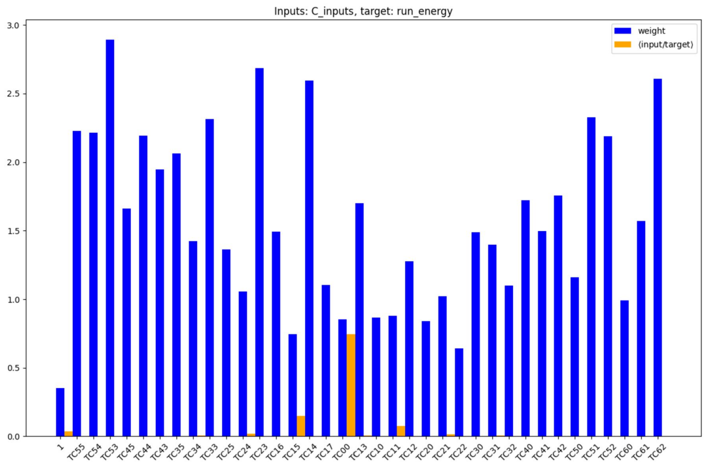
Run number	Run energy [GeV]	Total efficiency %	n. events (after selections (kevt))
786	10	43.44	16.6
766	20	54.94	22.2
772	30	55.56	22.8
774	40	51.27	20.7
775	60	48.26	19.6
776	80	44.29	18.7
778	80	43.84	17.8
779	100	40.44	61.6

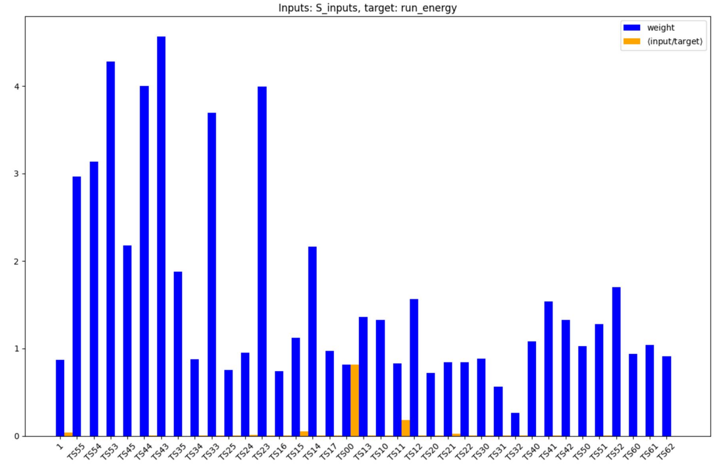




Data calibration

- We **calibrate** the energy optimizing an **affine transformation** of the inputs (Ax + b).
- We select **randomly 5000 events** at each energy as a data set for calibration.
- The calibration process is performed separately for Cherenkov and Scintillating energies.
- The **calibration inputs** are the 36 tower values and the **calibration target** is the run energy.
- For each signal, we apply a **least-squares linear optimization** which determines the best-fitting weights that map the inputs (=energy measured in each tower) to the target (=run energy).
- In the following plots, we visualize in blue the results of the calibration: the **weights** assigned to each tower.
  - The weights extracted from the calibration are **the same** for all energy values.
- In orange we plot how each input data (= TS or TC values) relates to the target value (=run energy) on average.





Resolution and Weights

In the following table, we summarize the key values for data analysis.

The overall energy resolution is calculated using a weighted average, with the weighted average energy defined as

$$\bar{x} = \frac{x_C w_C + x_S w_S}{w_C + w_S} = \frac{x_C \frac{1}{\sigma_C^2} + x_S \frac{1}{\sigma_S^2}}{\frac{1}{\sigma_C^2} + \frac{1}{\sigma_S^2}}$$

Run Energy [GeV]	Energy resolution %		Weights (*10^(-2))		Combined energy resolution %
	Scintillating signal	Cherenkov signal	Scintillating signal	Cherenkov signal	
10	7.4	10.2	1.8	0.96	6.3
20	5.7	7.2	3.1	1.9	4.7
30	4.9	6.0	4.2	2.7	4.1
40	4.5	5.4	3.3	5.0	3.8
60	4.0	5.0	3.9	6.3	3.5
80	3.8	4.6	4.8	7	3.2
100	3.6	4.3	5.3	7.7	3.1

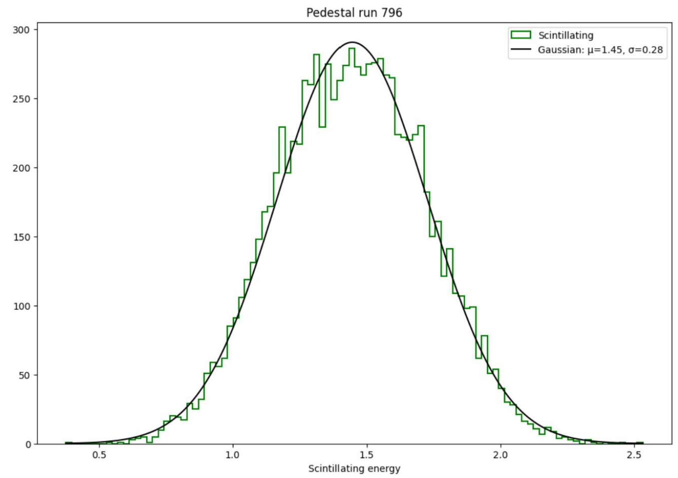
Fitting Processes

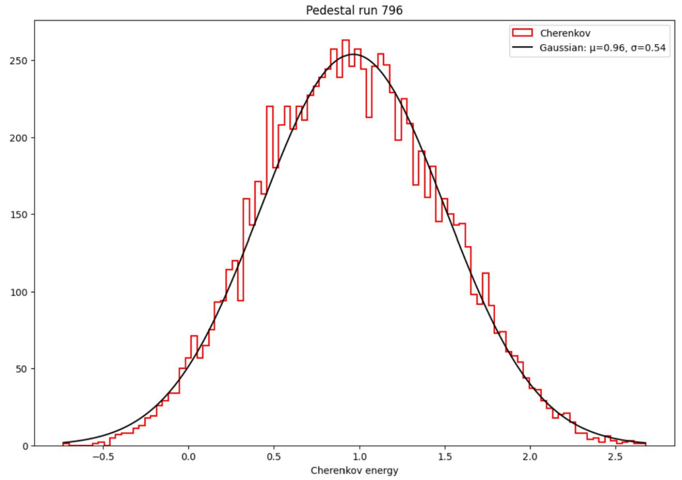
- We want to compute the **resolution** of the calorimeter at the nominal energy for the run. To avoid residual bias to influence the resolution, we consider the ratio $r = \frac{\langle E_{\mathrm{calib}} \rangle}{E_{\mathrm{run}}}$
    - We then study the resolution for $E_{\mathrm{corr}} = \frac{E_{\mathrm{calib}}}{r} = \frac{E_{\mathrm{calib}}}{\langle E_{\mathrm{calib}} \rangle / E_{\mathrm{run}}}$
- We estimate the resolution, defined as $\frac{\sigma_E}{E_{\mathrm{run}}} = \frac{\mathrm{IQR}/1.349}{E_{\mathrm{run}}}$, for:
    - Scintillating and Cherenkov energy,
    - S+C average energy and S+C weighted average energy.
- We perform a **resolution fit** to extract the resolution parameters according to $\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$ with fixed noise term
- For more info on the data calibration and fitting process: https://indico.cern.ch/event/1487788/contributions/6271611/subcontributions/519012/attachments/2984957/5257046/Report%2011-12-24%20(1).pdf

Noise analysis

- To estimate the noise, we choose the **σ_{68}** derived from the **total energy measurement** in the **calibrated pedestal runs**, as it provides an accurate representation of the noise.
- In the plots I have overlaid a theoretical Gaussian, with a standard deviation equal to the **σ_{68}** of the noises to show that the **noise follows a Gaussian distribution** and that **σ_{68}** serves as a **reliable estimator** of the noise.

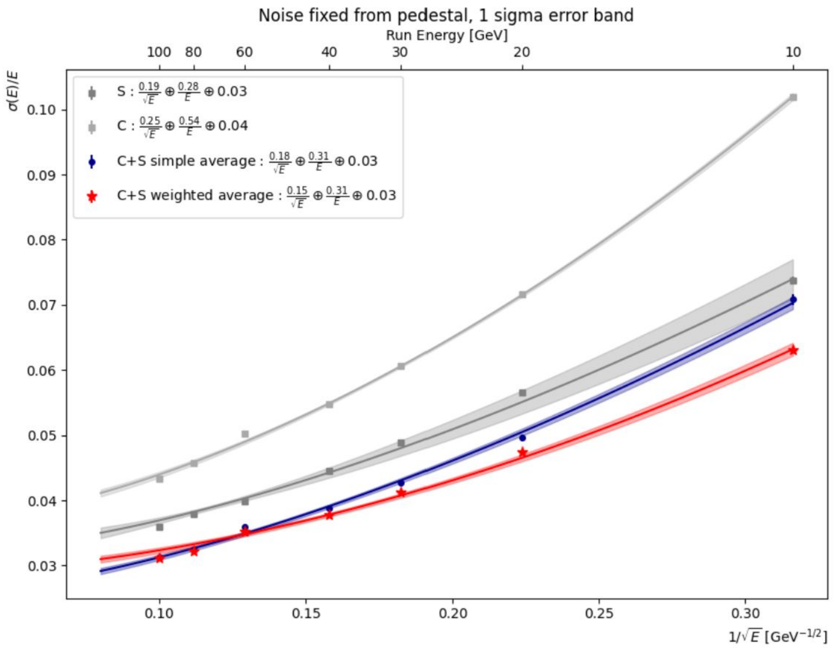
Run number	σ_{68} S [GeV]	σ_{68} C [GeV]
767	0.29	0.54
781	0.28	0.53
796	0.28	0.54





Fixed noise fit

- The values of b are set using the σ_{68} of the calibrated pedestal runs.
- A **1-sigma** error band is drawn around the fitted curve to visualize the uncertainty of the fit.
- The error band was calculated using toys generated with the values from the fit (including the covariance) (100 samples).



	a (10^-3)	error on a (10^-3)	error %	b (10^-3)	c (10^-3)	error on c (10^-3)	error %	a-c correlation
S	193	1	0.5	280	31.2	0.31	1	-0.752
C	249	1	0.4	540	35.8	0.35	0.99	-0.792
average	184	0.8	0.4	310	25.2	0.26	1.1	-0.753
weighted average	149	0.7	0.5	310	28.8	0.22	0.8	-0.812

Bootstrap to compute uncertainties

Bootstrapping involves generating multiple datasets by randomly sampling from the original dataset with replacement, to observe how the model parameters might vary. A **summary** of how it works:

- **Generating parameters:** We generate 100 sets of parameters (resolutions) sampled from a multivariate normal distribution, based on the original model's parameters and the covariance matrix.
  - This step **simulates new experiments** with different parameter values.

- **Re-evaluating the resolution with bootstrapped parameters:** For each set of bootstrapped parameters, the model is re-evaluated using the resolution fit formula. This results in a list of predicted values of the resolution fit parameters (a, c) for each bootstrapped parameter set. (**Note**: we consider b fixed)

- **Estimating the error:** The standard deviation of the bootstrapped model outputs (a, c) is calculated along the y-axis to estimate the uncertainty in the model's predictions. This standard deviation represents the **variability of the model's output** due to the uncertainty in the parameter values.

- **Plotting the error band:** the error band is drawn around the fit. The filled region represents the range of predictions within one standard deviation of the bootstrapped results. This visualizes the uncertainty in the fit due to variations in the model parameters (a, c).

- **Further info:** https://scikit-hep.org/iminuit/notebooks/error_bands.html